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INTERPRETING PATTERNS OF LAKE ALKALINITY IN THE UPPER MIDWEST REGION, USA

by

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16. ABSTRACT

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Abstract

To clarify the extent of sensitivity of surface waters to acidic deposition in Minnesota, Wisconsin, and Michigan, we have mapped patterns of lake and stream alkalinity. We analyzed data from approximately 14,000 lakes and streams and evaluated the apparent spatial associations between these data and macro-scale factors thought to influence alkalinity (such as land use, land forms, hydrology, geology, and soils) to aid in extrapolation of the data. The level to which each factor is important in influencing alkalinity varies within the region. Our map helps meet the urgent need to understand the relative potential sensitivity of surface waters in the Upper Midwest, provides a tool for selecting geographic areas for more detailed studies, and allows more accurate regional assessments of effects of acidic deposition on aquatic resources.

A major goal specified in the National Acid Precipitation Assessment Plan (Interagency Task Force on Acid Precipitation, 1982) is to quantify the extent of sensitivity of the nation's lakes and streams to acidification. Early efforts to determine patterns of surface water sensitivity to acidic deposition relied on interpretations of bedrock distribution and chemistry (Galloway and Cowling, 1978; Likens et al., 1979; Hendrey et al., 1980; National Atmospheric Deposition Program, 1982). Other efforts were based on soil sensitivity (McFee, 1980) and surficial geology (Shilts, 1981). Although these studies contributed to the general knowledge of the extent of surface water sensitivity, they are in sharp disagreement for many portions of the country. More importantly, there is a lack of spatial correlation between the patterns drawn by these efforts and the observed patterns of surface water alkalinity. Alkalinity is commonly used as an index of potential sensitivity because it expresses, in part, the acid-neutralizing capacity of water bodies and thus their relative tolerance or potential sensitivity to acidic inputs.

It is apparent that maps of rock type or soil type alone are inadequate to express patterns of surface water sensitivity. Results from several recent studies of surface water sensitivity in different regions of the United States (Eilers et al., 1983; Haines and Akielaszek, 1983; Twaroski et al., 1984) indicate that no single factor (e.g., bedrock geology) can explain observed patterns of surface water alkalinity. Rather, a variety of factors affect alkalinity, such as land use, physiography, soil type, and geology, and the relative importance of any one, or a particular combination of those factors, may vary within or among regions.

With this rationale, we approached the problem of depicting the likely patterns of surface water sensitivity in the Upper Midwest by synoptically analyzing spatial patterns of surface water alkalinity as an integrator of the

various factors that determine sensitivity. We accomplished this by: (1) assembling available alkalinity data on as many surface waters as possible; (2) plotting these data on relatively large-scale maps; and (3) analyzing the patterns of the values of the plotted data for spatial correlations with other characteristics such as land use, geology, and physiography.

Alkalinity is certainly the most readily available measure of the acid-neutralizing capacity of surface waters; however, the actual response of a given lake or stream to acidic input is determined by numerous biogeochemical and hydrological factors of the watershed plus chemical processes within water bodies. Although alkalinity values do not completely incorporate the influences of all factors into a definition of surface water sensitivity, they do provide a reasonable basis for determining spatial patterns of relative potential sensitivity at regional and national scales.

A national map compiled earlier (Omernik and Powers, 1983) described the general patterns of surface water alkalinity in the conterminous United States. By comparison, our regional map is based on one hundred times more data for the Upper Midwest and depicts the spatial patterns of surface water alkalinity in greater detail than was possible in the national map.

Our purpose is to show the range of alkalinity that might be expected in most of the surface waters most of the time. Relative to the national map, the regional map provides more detailed ancillary information on ranges of conditions, on significant apparent regional and local relationships between alkalinity and macro-scale watershed characteristics such as land use and physiography, on seasonal variations, and on other factors (Omernik and Griffith, 1985). This information in turn provides a basis for understanding the confidence with which predictions and estimations of potential surface water sensitivity might be made for the region, or parts of the region. We

emphasize, however, that the map and the ancillary information are not intended for making precise predictions of sensitivity for individual water bodies or specific locations. Rather, the regional maps are intended to help fill the urgent need to understand the relative potential sensitivity of surface waters in different parts of the country in order to provide a national perspective of the potential problem, provide rationale for selecting geographic areas for more detailed studies, and allow more accurate regional assessments of acidic deposition impacts on aquatic resources.

MAP DEVELOPMENT

The methods used to develop our map were similar to those used to prepare the other regional alkalinity maps (Omernik and Kinney, 1985; Omernik and Griffith, 1986). We analyzed each data point for representativeness by keeping the watershed size consistent with the relative homogeneity of major watershed features thought to influence surface water alkalinity. Most of the data were associated with small watersheds less than 130 sq km (50 sq mi). We excluded data with watersheds larger than 2600 sq km (1000 sq mi). Representative data were imperative for detecting spatial patterns of alkalinity and possible correlations with patterns of other characteristics, and for extrapolation of the data. Inclusion of data from sites having large watersheds of widely differing characteristics, or data downstream from major industrial waste discharges, would mask these spatial patterns.

The map of the Upper Midwest Region was based on patterns of the actual alkalinity values and the apparent spatial associations of these values with areal characteristics that are believed to be causal or integrating factors affecting alkalinity. Causal factors, as used in this paper, refer to those factors that generally affect alkalinity directly (e.g., geology and soils).

Integrating factors, on the other hand, are those factors that reflect combinations of causal factors; for example, land use and potential natural vegetation reflect regional combinations (or an integration) of causal factors such as soils, land surface form, climate, and geology. We believe that the importance of each of these factors, and the hierarchy of importance relative to the combinations of factors, varies from one region to another and even within regions. Clarifying these regional factors is a major goal of our overall synoptic analyses.

We acquired alkalinity data from a variety of sources. The most recent data (1978-1983) for the Upper Midwest Region were obtained from STORET, an EPA computer-based water quality data storage and retrieval system, and from several other sources (Glass et al., 1983; Twaroski et al., 1983; Thornton et al., 1982; and Heiskary and Thornton, 1983). These data were plotted on 1:250,000 or 1:500,000-scale topographic maps, with each site represented by a small circle color-coded to an alkalinity class value; the exact value and the water body type were noted beside the circle. STORET data for an earlier period, mostly from the early 1970s, were plotted on overlays. These combined sources yielded values for approximately 1,648 sites (86% from lakes and 14% from streams) in the Upper Midwest Region.

For Michigan and Wisconsin, we relied heavily on earlier (1960 to 1975) data, because of a paucity of more recent data and the relatively complex alkalinity pattern. In Michigan's Upper Peninsula, patterns of historical data from Schneider (1975) indicated the location of clusters of lakes with less than 400 ueq/l alkalinity. By superimposing these patterns on our 1:250,000 and 1:500,000-scale maps containing the more recent alkalinity data, and by noting the apparent relationships of lake type to alkalinity, lake size to alkalinity, lake vs. stream alkalinity, and relevant macro-scale watershed

characteristics, we were able to interpolate and estimate areas of specific alkalinity classes.

For Wisconsin, an abundance of historical alkalinity data was available in publications of "Surface Water Resources" by county (Various Authors, 1960-1980). These included maps with an alkalinity classification for each lake and stream sampled. For the eighteen-county area delineated in our map inset, alkalinity values were given for about 10,500 lakes and 2,500 stream sites. On these large-scale county maps, we color-coded lake and stream sites according to alkalinity class, and the resultant patterns indicated where boundaries might be drawn. The delineation of our alkalinity classes on the county maps was made after noting lake types, lake sizes, stream courses, and physical features from 1:250,000-scale topographic maps as well as consideration of other causal and integrating factors. In addition, comparisons were made to the spatial patterns of recent alkalinity data plotted on the 1:500,000-scale Wisconsin map.

The data for Minnesota used in our mapping were primarily of recent origin. Values from STORET, Glass et al. (1983), Twaroski et al. (1983), Thornton et al. (1982), and Heiskary and Thornton (1983) were plotted on 1:250,000-scale topographic maps by alkalinity class (e.g., 1 = < 50 ueq/l, 2 = 50 to 100 ueq/l, 3 = 100 to 200 ueq/l, etc.). An interpretive process similar to that used for Wisconsin and Michigan was also used for Minnesota. Since the relationship between alkalinity and lake type and lake size is quite different in northeast Minnesota than in other parts of the Upper Midwest Region, the final class boundaries there were based largely on the spatial pattern of the alkalinity data itself, but also with some considerations of bedrock type, land surface form, and land use.

One area of concern is the use of single sample values as representative data points. Since the alkalinity of surface waters can fluctuate on a daily, weekly, monthly, and annual basis, a single sample from a water body may not seem to be representative of that lake or stream's average alkalinity. We believe, however, that for the purposes of this map, one-sample data points are sufficiently representative for a macro-scale assessment of the spatial patterns of surface water alkalinity. The more data we plotted, no matter what the sample month or number of samples, the more confidence we had in extrapolating and drawing the class boundaries. If a single sample appeared to be anomalous, more scrutiny was given to the data source, methodology, sample month and year, and location.

When making our final interpretations and map unit delineations, we also estimated approximate correction factors for the data to compensate for the probable bias introduced by the different methodologies used in measuring alkalinity (Jeffries and Zimmerman, 1980; Henriksen, 1982; Kramer and Tessier, 1982; Church, 1984). A more detailed discussion of these data considerations and of the temporal variations of our alkalinity values is given in Omernik and Griffith (1985).

Spatial patterns of the alkalinity values were the most important factor for delineating alkalinity map units. Land use and vegetation information were also useful for delineating areas where low alkalinity waters were unlikely. Low alkalinity waters are generally found only in predominantly forested or wetland areas. Wherever agriculture (including grazing) occurs, even as a small portion of the land use mosaic, mean annual alkalinity values are commonly well over 400 ueq/l. Geology maps were used to focus our attention and data collection efforts on areas of suspected sensitive rock types.

However, final map unit alignments were nearly always based on patterns of

alkalinity values or physiographic features. For most of the Upper Midwest Region, bedrock by itself was not a good indicator of surface water alkalinity. Locally, physiographic and hydrologic features were often very helpful for map unit delineations.

REGIONAL PATTERNS

The Upper Midwest Region exhibits great diversity and spatial heterogeneity in its patterns of surface water alkalinity. Several factors contribute to the complexity of these patterns, especially lake types, sizes, and hydrologic characteristics; bedrock types; land surface forms; and soil characteristics. The formation of these lakes, surface features, and soils reflect the region's glacial history. As a result of glacial action, this region contains one of the densest concentration of lakes in the world.

While a great majority of the lakes in the Upper Midwest Region have high mean annual alkalinity values (> 400 ueq/l), there are several areas where numerous lakes have low alkalinity values (< 50 ueq/l). Although large in number, the lakes in the lowest alkalinity class tend to be small in size and comprise a small percentage of the region's total surface water area (Table 1). The lakes of average alkalinity values < 200 ueq/l comprise approximately 6.6% of the region's surface water area. Clusters of lakes with alkalinities < 50 ueq/l are found in portions of Vilas, Oneida, Lincoln, and Langlade counties of Wisconsin, as well as Gogebic, Iron, Alger, and Chippewa counties of Michigan.

We divided the Upper Midwest Region into three subregions, based loosely on the associations of alkalinity and the physical characteristics of lakes and streams and their watersheds. These subregions, while individually containing variations in surface water alkalinity, can be broadly differentiated by certain causal or integrative spatial factors that influence the alkalinity

Table 1. Area (hectares) in lakes by alkalinity class.*

Alkalinity Class	Wisconsin	Minnesota	Michigan	Total
< 50 ueq/l	6,400	0	1,686	8,086 (0.4%)
50 - 100	5,595	13,982	1,426	21,003 (1.1%)
100 - 200	17,843	68,423	8,948	95,214 (5.1%)
< 200	29,838	82,405	12,060	124,303 (6.6%)

Total lake area in the Upper Midwest Region (Northern Wisconsin, Northeastern Minnesota, and Northern Michigan) 1,868,799 hectares

* Lakes > 6 hectares (15 acres). Based on extent of surface water appearing on 1:250,000-scale USGS topographic maps.

patterns. Factors that can directly affect alkalinity such as geology, land surface form, and soils, show subtle variations in the different subregions. Integrating factors such as potential natural vegetation, or especially land use, which generally correlated with alkalinity in other parts of the nation (Omernik and Powers, 1983), were of less importance for determining alkalinity patterns in the Upper Midwest Region. Distinctions can be made between: (1) most of northern Wisconsin and east central Minnesota; (2) northeast Minnosota comprising Cook, Lake, and St. Louis counties; and (3) the major portion of Michigan's Upper Peninsula and the northern portions of Bayfield, Ashland, and Iron counties in Wisconsin (Figure 1). Although the individual subregions are not completely homogeneous, they provide a basis for analyzing and comparing the differences between areas of low alkalinity.

Wisconsin-East Central Minnesota

In the northern Wisconsin-east central Minnesota subregion, the differences in lake types [without inlets or outlets (Type A), with inlets or outlets

Figure 1. Subregions of the Upper Midwest Region.

(Type B), spring-fed, acid bog, alkaline bog], and the large number of lakes of each type, contribute to the extreme heterogeneity of surface water alkalinity. While most of the lakes without inlets or outlets are of low alkalinity, the spring-fed lakes, and lakes with inlets or outlets are generally of high alkalinity. The continental glaciation left a relatively thick layer of glacial drift over this part of the Upper Midwest, and most of the lakes occur in pitted outwash and end moraines. These lakes are usually situated well above bedrock and are relatively shallow. For example, in Oneida County, Wisconsin, 88% of the lakes are less than 7.6 meters deep (Andrews and Threinen, 1966). Apparently, for much of this subregion, bedrock has very little influence on lake chemistry and lake morphology.

The major land forms in this subregion include outwash plains, ground moraines, end moraines, lacustrine plains, and drumlins. In the Minnesota portion, in particular Carlton, Crow Wing, and Itasca counties, Twaroski et al. (1984) concluded that land forms seem to exert a greater influence on lake chemistry and lake morphology than does bedrock. They found that, based on slope and soils, moraine areas are most likely to contain low alkalinity lakes.

These lakes are generally small, with no inlets; are located in interfluvial areas; are surrounded by steep slopes and soils that create a quick release of water to the lake; and receive no groundwater inflow (Twaroski et al., 1984).

Although Twaroski et al. (1984) found that lakes tended to have high alkalinities in outwash plains in east central Minnesota, many of those portions of Wisconsin within our map unit #1 (< 50 ueq/l) and map unit #2 (50-100 ueq/l) are found in outwash plains and in end moraines. The difference between moraines and outwash plains appears to be of less importance for lake alkalinity in this subregion than more specific factors such as groundwater contact, lake size, watershed size, stream inflow and outflow, soil texture and mineralogy, and local relief. High alkalinity lakes tend to be large, with significant inlets and outlets, with large watersheds, and with substantial groundwater contact. A key factor affecting the alkalinity of lakes in this subregion is hydrology, or the route and residence time of water in the watershed (Eilers et al., 1983; Twaroski et al., 1984; Schnoor et al., 1986). The relationship of groundwater to lakes is of major importance (Anderson and Bowser, 1986) and helps to explain why high alkalinity lakes are found in close proximity to low alkalinity lakes, but it is the least known aspect of lake hydrology (Winters, 1977).

Several areas of surface waters with mean annual alkalinity < 50 ueq/l are found in this subregion, centered around Vilas and Oneida counties, Wisconsin. These areas contain clusters of low-alkalinity lakes without inlets or outlets (Type A). Although the number of lakes in these areas is generally large, the total area of surface water is relatively low since Type A lakes tend to be small in size. For example, of the 1,327 lakes in Vilas County, Wisconsin, 776 (59%) are Type A lakes less than eight hectares, but these account for only 4% of the county's lake area (Table 2). On the other hand, only 88 (7%) of the

Table 2. Characteristics of lakes in Vilas County, Wisconsin. Alkalinity values were determined by single endpoint titration (colorimetric -- methyl orange) and, although reported in mg/l, have been converted to ueq/l in the table. Source: Black et al. (1963).

Size Class Hectares	Lake Type A (Without inlets or outlets)					Lake Type B (With inlets or outlets)					Spring Lakes				
	#	Mean Size (ha.)	Total Hectares	Sampled lakes: Mean Alk.	#	#	Mean Size (ha.)	Total Hectares	Sampled lakes: Mean Alk.	#	#	Mean Size (ha.)	Total Hectares	Sampled lakes: Mean Alk.	#
0-7	776	2.0	1554 (4%)	174	493	31	2.3	72 -	449	23	97	1.6	158 -	693	27
8-23	145	13.6	1969 (5%)	136	145	24	15.1	362 (1%)	546	22	13	15.6	203 -	626	12
24-39	35	31.1	1089 (3%)	172	35	19	30.6	581 (2%)	640	19	12	32.3	388 (1%)	988	8
40-80	32	55.2	1767 (5%)	158	31	27	58.3	1574 (4%)	678	27	8	60.9	487 (1%)	772	8
81-201	13	117.2	1523 (4%)	386	12	38	127.8	4858 (13%)	756	38	9	108.5	977 (3%)	902	9
202-404	6	285.9	1716 (5%)	332	6	26	286.9	7461 (20%)	762	26	2	210.6	421 (1%)	720	2
405-808	1	-	582 (1%)	40	1	9	504.4	4540 (12%)	830	9	-	-	-	-	-
809	-	-	-	-	-	4	1299.6	5198 (14%)	700	4	-	-	-	-	-
Total	1008	10.1	10,200 (27%)	170	723	178	138.5	24,646 (66%)	664	168	141	18.7	2,634 (7%)	755	66

lakes in the county are Type B lakes or spring lakes greater than 80 hectares, yet these types comprise 63% of the county's lake area. Thus, for Vilas County, the greatest extent of lake area is in the higher alkalinity classes, and the average (uncorrected methyl orange) alkalinity of 298 ueq/l (Black et al., 1963) is skewed downward by the large number of low alkalinity but small Type A lakes.

The largest area of lakes with alkalinities < 50 ueq/l is located in Oneida County, Wisconsin, and contains 109 named Type A lakes ranging from 0.8 hectares to 425 hectares in size. The mean size of these 109 lakes is 27 hectares, and the median size is 12 hectares. Most of this area occurs in a pitted glacial outwash plain, with sandy acidic soils of low fertility that typify much of Oneida County.

Northeast Minnesota

The northeast Minnesota subregion includes Cook, Lake, and northeastern St. Louis counties, and exhibits considerably more homogeneity in surface water alkalinity than the other subregions. Lakes of various types and sizes tend to have more similar alkalinity values. An extremely high density of lakes and extent of area in lakes characterizes this subregion.

A wide variety of bedrock types is found in this subregion, and because the soil and glacial till are relatively shallow, bedrock appears to have a greater influence on lake morphology and lake chemistry. In general, the gabbros, granites, and iron formations contain lakes with relatively lower mean alkalinity values, mostly less than 200 ueq/l (Twaroski et al., 1984). These formations are non-calcareous and resistant to weathering, with thin overlying soils that provide little buffering capacity to the lakes. The slates and greenstone formations contain lakes of higher alkalinity, mostly 400 ueq/l or greater, and, although generally non-calcareous, have some veins of calcite that may greatly influence lake sensitivity (Heiskary and Thornton, 1983). Some calcareous soils are found in the Ely greenstone northeast of Ely, as well as in the large area west of St. Louis County that corresponds to deposits from glacial Lake Agassiz. In addition, the slates and greenstone have faults and fractures which may supply groundwater to these areas of higher alkalinity (Twaroski et al., 1984). For most of this subregion, however, groundwater resources are limited due to the shallow drift and Precambrian crystalline bedrock types and do not affect alkalinity as in Wisconsin or central Minnesota.

Alkalinity values within each of our four classes appear to be independent of lake type and lake size in the northeast Minnesota subregion. Whereas we found that the larger lakes had higher alkalinity in Wisconsin, Heiskary and

Thornton (1983) showed no significant correlation between lake surface area and alkalinity in their northeast Minnesota study area. A mix of lakes without inlets or outlets (Type A), with inlets and outlets (Type B), and with outlets but not inlets are found in the low-alkalinity areas. For lakes sampled in our map unit #2 areas (50-100 ueq/l), the lake sizes ranged from 8 hectares to 1,255 hectares. The mean lake size was 242 hectares and the median size was 156 hectares.

The two smaller areas classified in the 50-100 ueq/l alkalinity range class on our map are located on the Duluth gabbro bedrock, which Heiskary and Thornton (1983) showed to have the lowest mean alkalinity of the various "bedrock geoprovinces" in the northeast subregion. The third 50-100 ueq/l class area is located on the Algoman granite bedrock, another non-calcareous area where surface water alkalinity is generally low. In northeast Minnesota, soil and glacial till are very shallow, and there appears to be some association between alkalinity and bedrock type (Rapp et al., 1985). Relatively local variations within each bedrock geoprovince, however, can have a significant influence on water chemistry. Small amounts of limestone, veins of calcite, or ancient glacial lake deposits may increase the buffering of otherwise sensitive bedrock.

Upper Michigan

The third subregion -- most of the Upper Peninsula of Michigan, and the extreme northwest portion of Wisconsin in Bayfield, Ashland, and Iron counties -- is physically more heterogeneous, with fewer lakes than the other subregions, and wide variations in surface water alkalinity. Most of the lakes occur in glacial outwash plains and moraines, although a few are found on bedrock outcrops and on ancient lacustrine deposits.

The eastern part of the peninsula is characterized by sandy and silty surficial features from the predominant ancient glacial lake bed deposits, with a mixture of alkalinity values. In the southeast part of the peninsula, some lakes are located on bedrock, but the presence of limestone results in high surface water alkalinities. The areas of lowest surface water alkalinity appear to be located in areas of glacial till, and the chemical and physical nature of this till, along with the amount of groundwater contact, drainage basin size, and lake type, greatly influence the degree of buffering capacity. The streams and lakes in these lower alkalinity areas are also located in the upper elevations of the watersheds. Many of the low alkalinity lakes are without inlets or outlets (Type A).

In the western half of the Upper Peninsula, most of the lakes occur in glacial till, and, as in Wisconsin, alkalinity values appear related to lake and watershed size, lake type, and the amount of groundwater contact. A few lakes are located on granitic bedrock in Baraga and Marquette counties, and these tend to be moderately low in alkalinity (100-200 ueq/l).

CONCLUSION

Our alkalinity map of the Upper Midwest Region illustrates the general patterns of the relative potential sensitivity of surface waters to acidic deposition. The map was developed through analysis of the spatial patterns of alkalinity values from over 14,000 lakes and streams, as well as through determination of apparent spatial associations between these data and various watershed characteristics believed to be causal. Alkalinity patterns in the region are extremely varied and complex. Many lakes have low alkalinities, but they tend to be small in size, comprise a small percent of surface water area, and occur in relatively small clusters. In northeastern Minnesota, however,

there are areas of low alkalinity in which all lakes regardless of size have similar values.

Development of this map reinforced the fact that a complex set of factors determines a water body's alkalinity. No single factor can explain regional patterns of surface water alkalinity. Also, the level of influence of these factors on alkalinity varies from one place to another. To compile the most accurate map possible necessitated developing a qualitative understanding of these regional patterns and spatial associations. Our cartographic expression of this understanding provides a tool and rationale for focusing research and survey activities in areas that are most likely to contain sensitive surface waters. Where complex variations in geology, land forms, soils, hydrology, and other factors affect surface water sensitivity, larger scale and more detailed studies will be necessary to clarify and quantify such relationships. We hope that the map will contribute to such studies and, ultimately, to a better understanding and management of our aquatic resources.

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Alkalinity Maps Available

The mapping of surface water alkalinity began in 1981 at the EPA's Environmental Research Laboratory in Corvallis, Oregon, as a first step in a comprehensive project to identify general patterns of potential surface water sensitivity to acidification. A "first cut" national map, based on data from approximately 2500 lakes and streams, was published in 1982. This map is available from the authors in Corvallis.

Since 1982, more detailed regional alkalinity maps have been developed. These larger-scale regional maps, based on alkalinity data from more than 24,000 lakes and streams, better illustrate the patterns in low alkalinity areas and provide rationale for selecting geographic areas for more detailed studies. The sampling design of the EPA's current National Surface Water Survey, for instance, is based heavily on these regional maps. Maps of the New England/New York Region, the Upper Midwest Region, and the Western Region are available in limited quantities from: The Center for Environmental Research Information, ORD Publications, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

The authors are currently involved in revising the alkalinity patterns for the eastern United States, using more data on larger scale maps. When this is completed, production of a revised national map is planned.